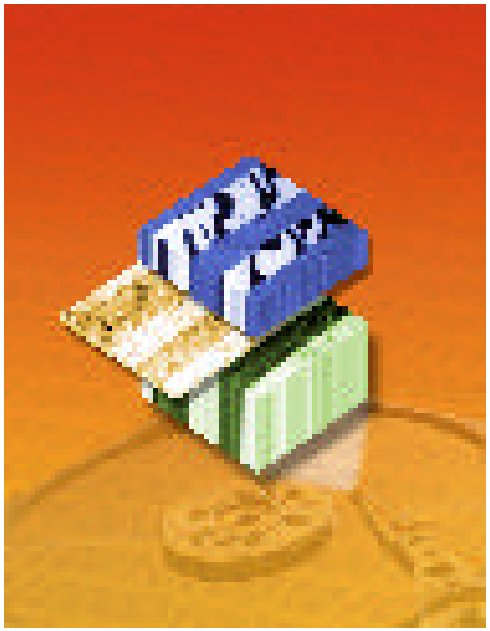
X-Ray Magnetic Linear Dichroism (XMLD) Spectromicroscopy.

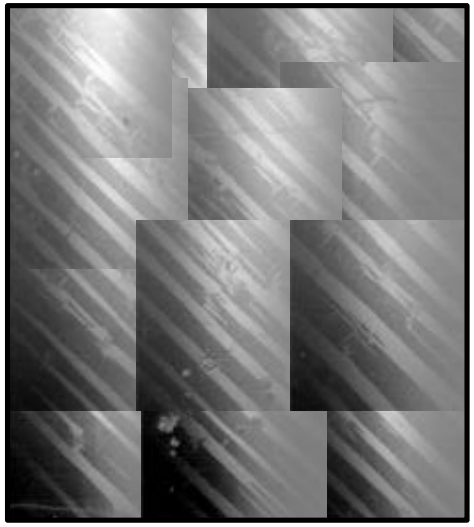


Compensated Magnetic Order at Surfaces.

SYSTEMS: Magnetic Multilayers - AFM Domains - AFM/FM Coupling

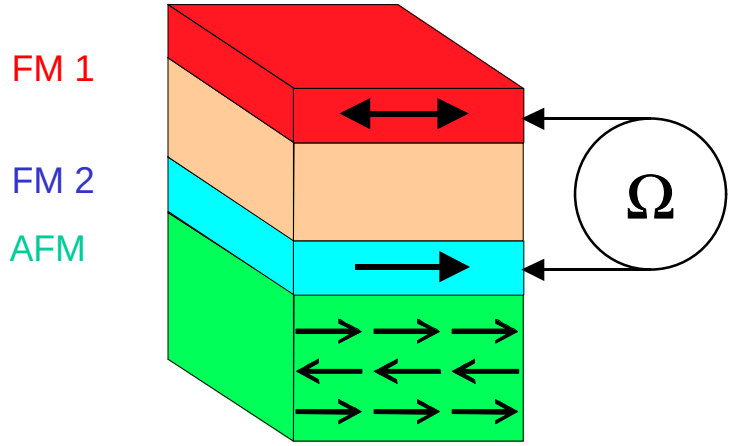
Antiferromagnetic

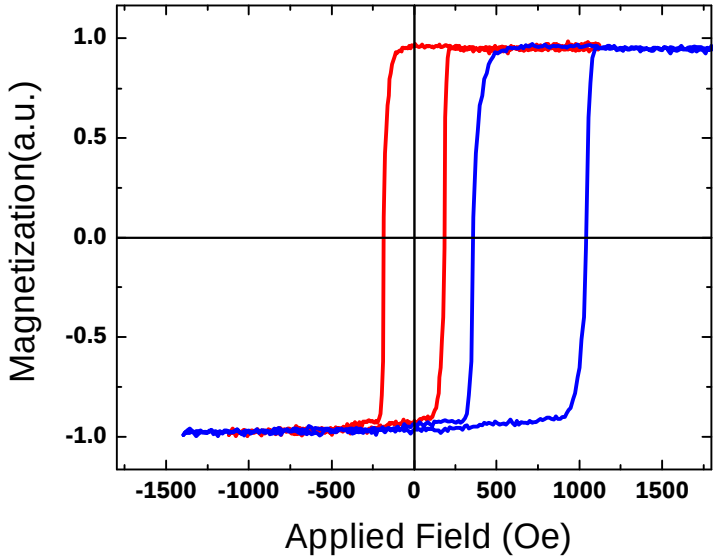
Domains



NiO(001) 300x300μm

Exchange Bias





WHY ? X-ray magnetic dichroism.

Classical “magnetic” methods

- MOKE, VSM, AFM …

… sensitive to a net magnetic moment (ferromagnet).

… are either bulk sensitive / qualitative / not element specific

- Neutron based techniques …

… sensitive to (un)compensated magnetic order.

… are classical bulk method (oz.).

- Second Harmonic Generation …

… only sensitive to coompensated order but not very well understood.

… highly surface/interface sensitive.

None of these techniques **combines**

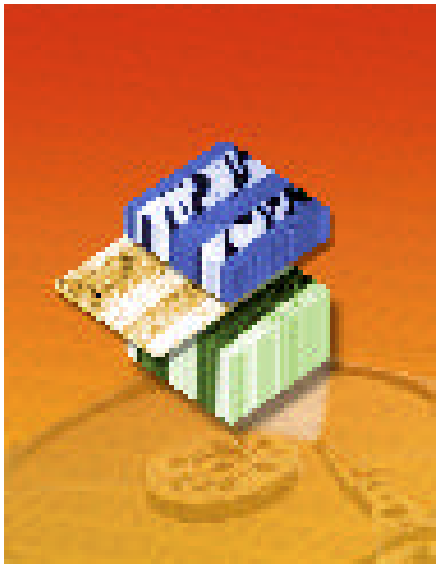
- surface/interface sensitivity
- element specifity
- sensitivity to compensated/uncompensated magnetic order

WHY ? X-ray magnetic dichroism.

X-ray absorption

… is surface and element specific (Fermis Golden Rule)

...is polarization dependent



- **XMCD …**

… probes uncompensated order (ferro/ferri **M**)

- XMLD ...

… probes compensated order (ferri/antiferro $\mathbf{M}^2$)

Photoemission Electron Microscopy has the spatial resolution (50-100nm) to resolve the relevant structures.

Basic Origins of Magnetic Dichroism

Magnetization causes symmetry breaking

- time reversal symmetry linear in M (chirality, +z is a distinct direction)

- 3-fold rotation around [111] linear in M^2 (anisotropy z is a distinct axis)

-Von Neuman: Symmetry breaking is reflected by a property tensor (optical conductivity)

Cubic system --- M along pos. z-axis --- M par. z-axis

$$\begin{pmatrix} \sigma_{xx} & 0 & 0 \\ 0 & \sigma_{xx} & 0 \\ 0 & 0 & \sigma_{xx} \end{pmatrix} \quad \begin{pmatrix} \sigma_{xx} & \sigma_{xy} & 0 \\ -\sigma_{xy} & \sigma_{xx} & 0 \\ 0 & 0 & \sigma_{zz} \end{pmatrix} \quad \begin{pmatrix} \sigma_{xx} & 0 & 0 \\ 0 & \sigma_{xx} & 0 \\ 0 & 0 & \sigma_{zz} \end{pmatrix}$$

XAS XMCD XMLD

QM Origins of Magnetic Dichroism

Optical transition rules:

$\Delta_l = +/-1$

orbital moment

$\Delta_j = 0, +/-1$

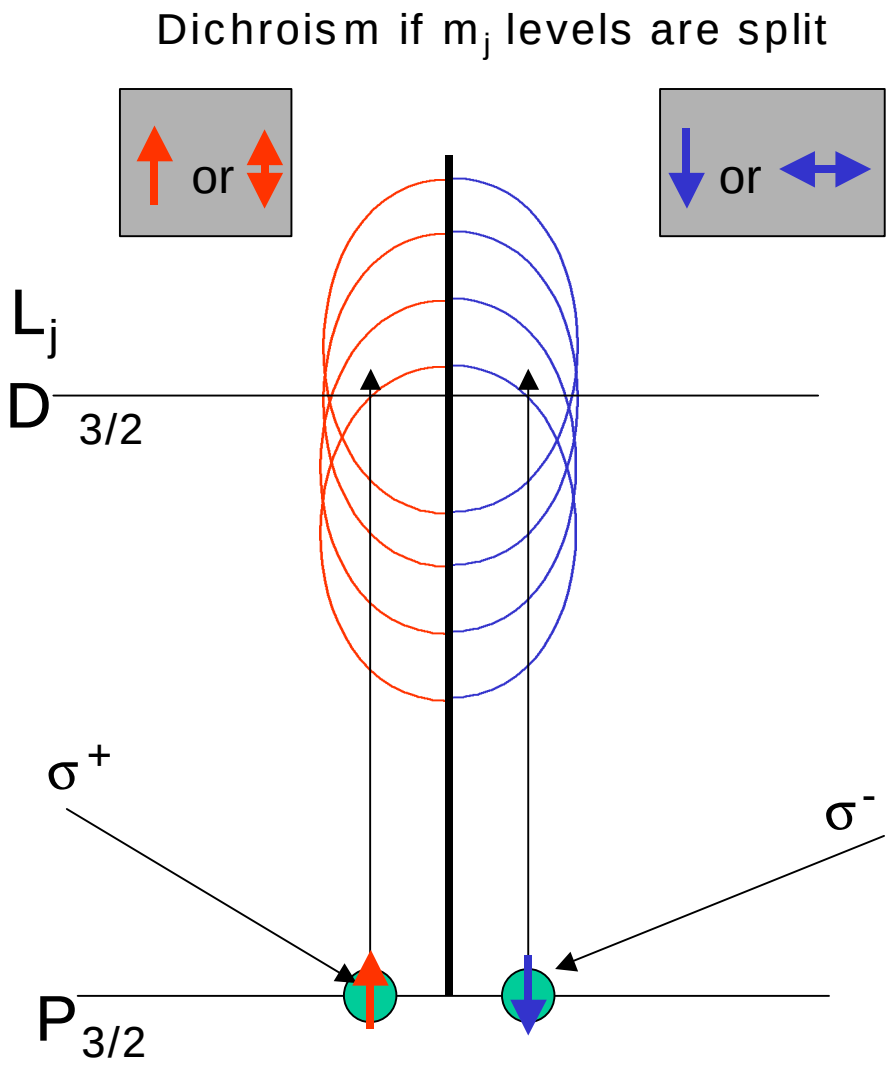
total moment

$\Delta_{mj} = +1(\sigma^+), -1(\sigma^-)$

projection on M

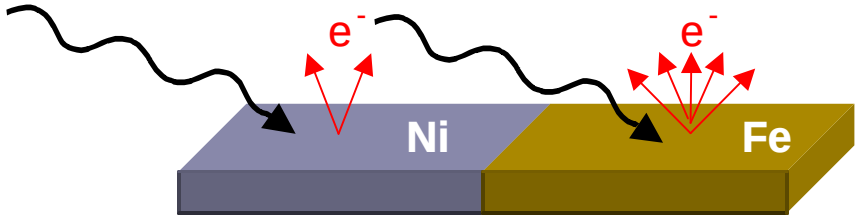
And magnetic splitting

→ Magnetic Dichroism

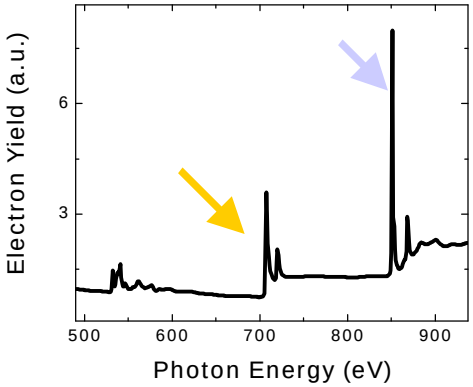


Polarization Dependent X-Ray Absorption Spectroscopy

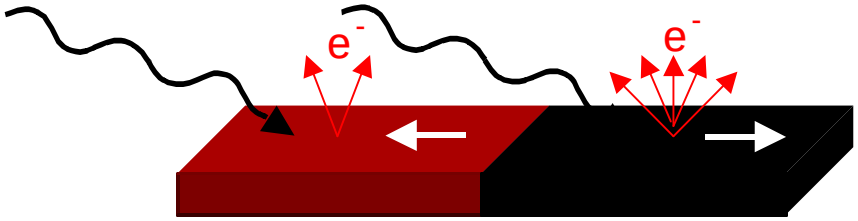
Absorption of monochromatic x-rays → Emission of electrons



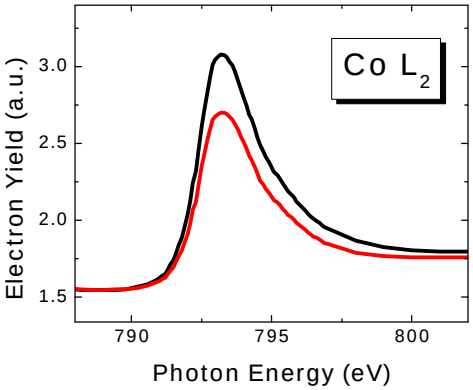
Chemistry



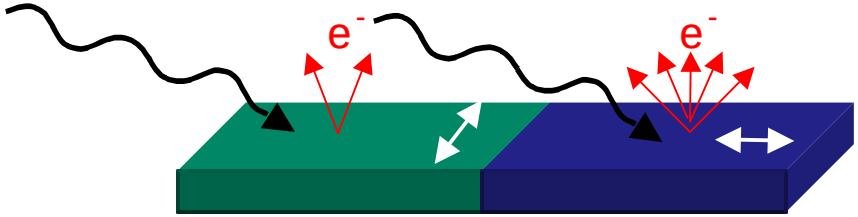
Circular polarization $\mu \sim \cos(\sigma, M)$



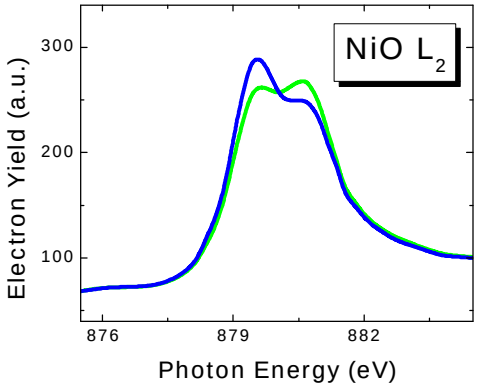
Ferromagnetism



Linear polarization $\mu \sim \cos^2(E, M^2)$



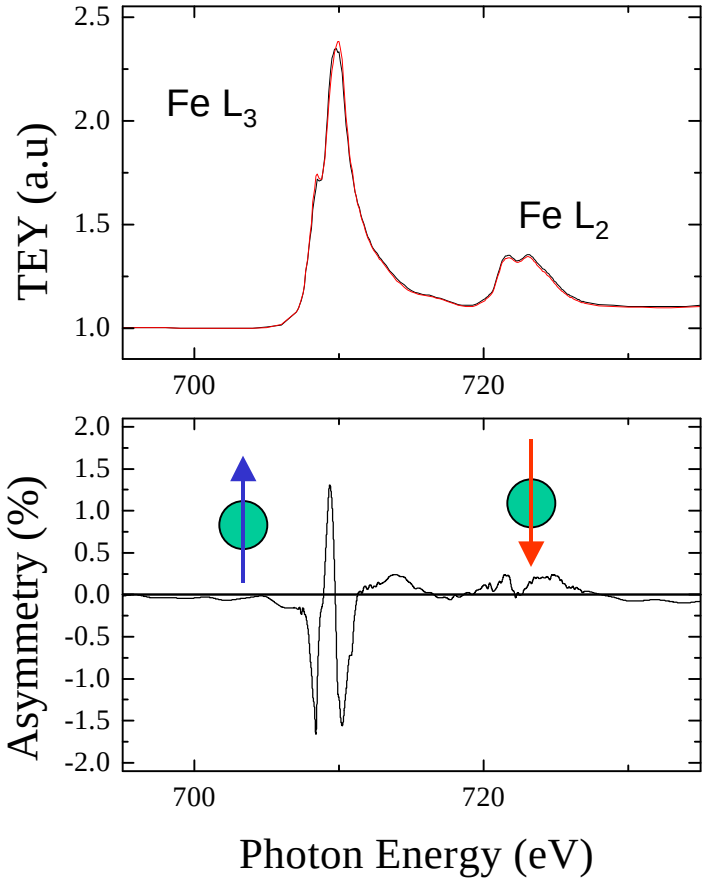
Antiferromagnetism



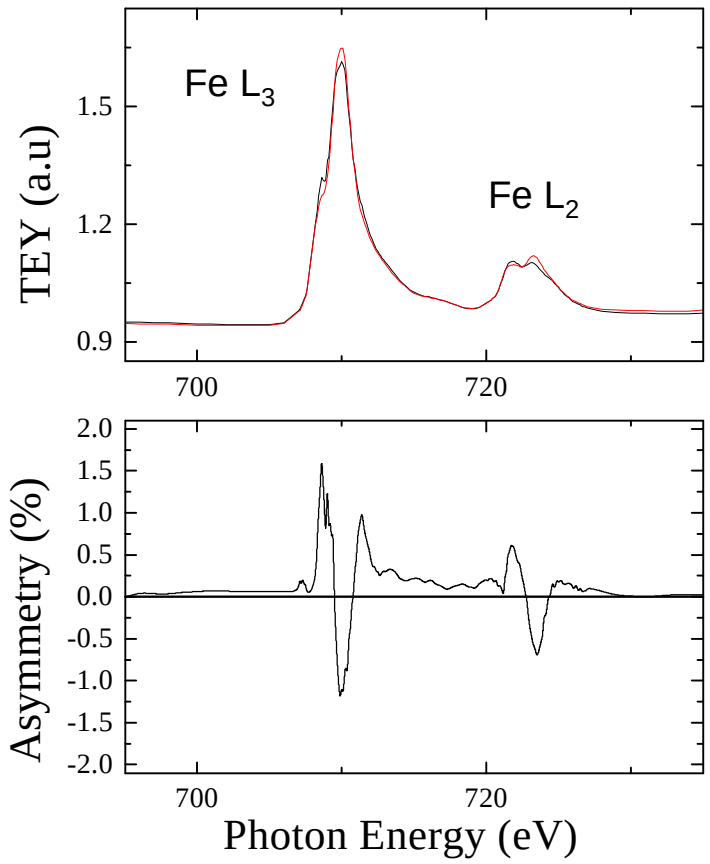
Information depth profile: $\exp(-\lambda t)$, where $\lambda = 2\text{nm}$

Comparison XMCD and XMLD: Ferrimagnetic Fe_3O_4

3 spins in unit cell: two up one down

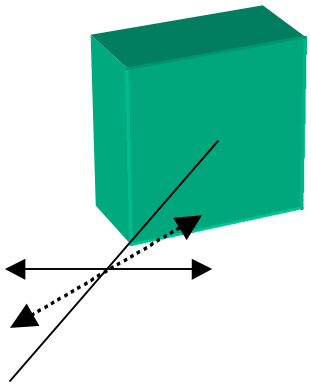


XMCD: L3 and L2 signature have opposite sign because the spins in the initial states are opposite.



XMLD: The sign of the moment does not matter. L3 and L2 signature are identical.

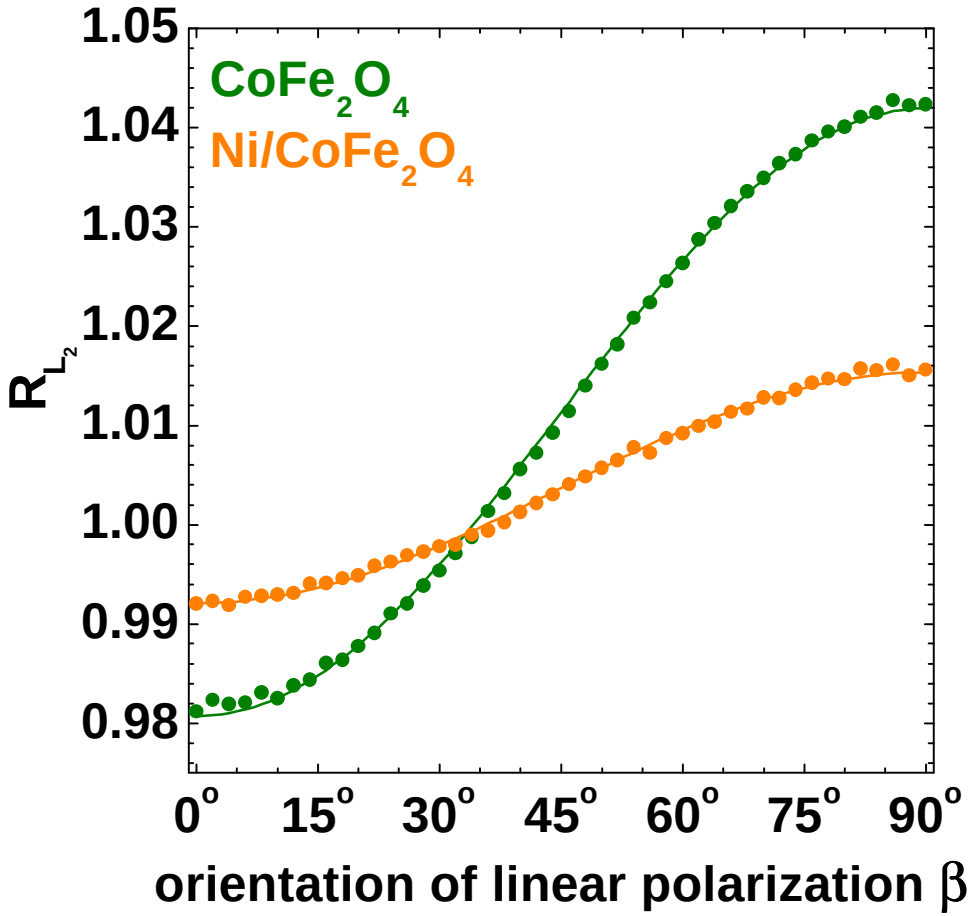
Angular Dependence of XMLD: $CoFe_2O_4$



Elliptical Polarizing

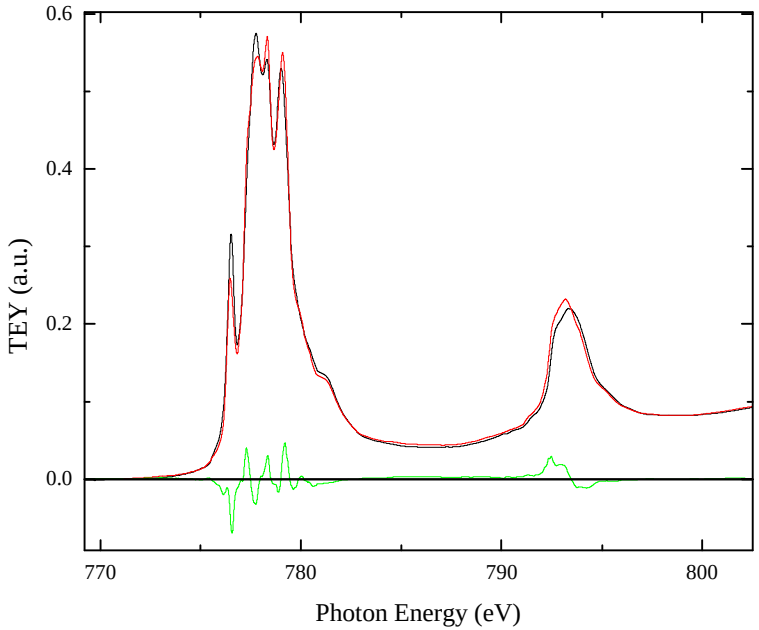
Undulator (Beamline 4, ALS):

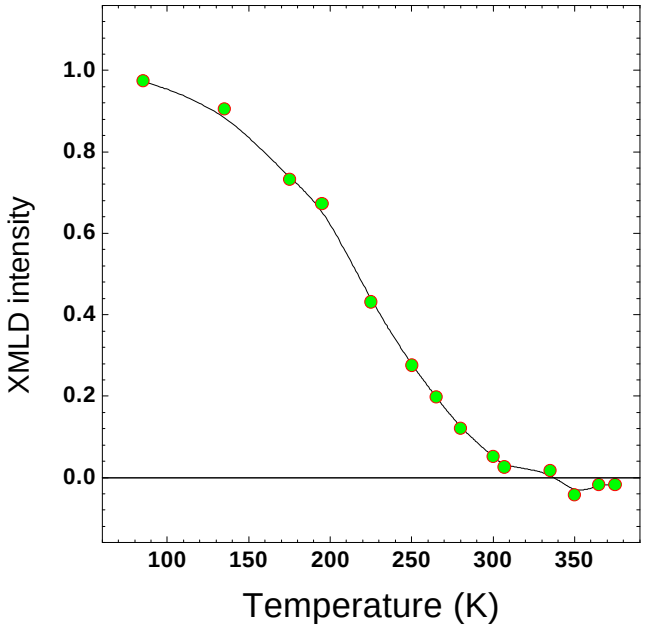
Variable Linear Polarization



If the XMLD extrema for a material are known the angle of the magnetic axes can be determined (compare to sum rules for XMCD)

Temperature Dependence of XMLD: CoO





CoO thin film (30nm). T_N is about the same as in the bulk. Each of the XMLD features can be used to determine T_N (300K).

Basic Features XMLD Spectroscopy

Intensity ratios within multiplets change with $\cos^2(\mathbf{E},\mathbf{M}^2)$:

Angular Dependence (Fe3O4) - direction of axes

They also change with $\mathbf{M}^2$ itself:

Temperature dependance (CoO)

Access compensated as well as uncompensated order:

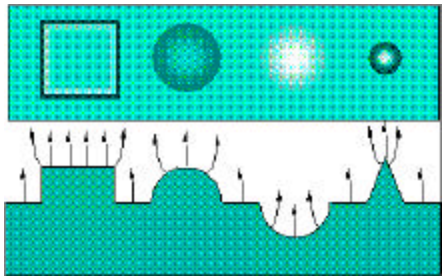
Ferrimagnets

Photoemission Electron Microscopy (PEEM)

- Electrostatic lenses (0-30kV) magnify local electron yield

- Elemental and magnetic contrast with 50-100nm resolution.

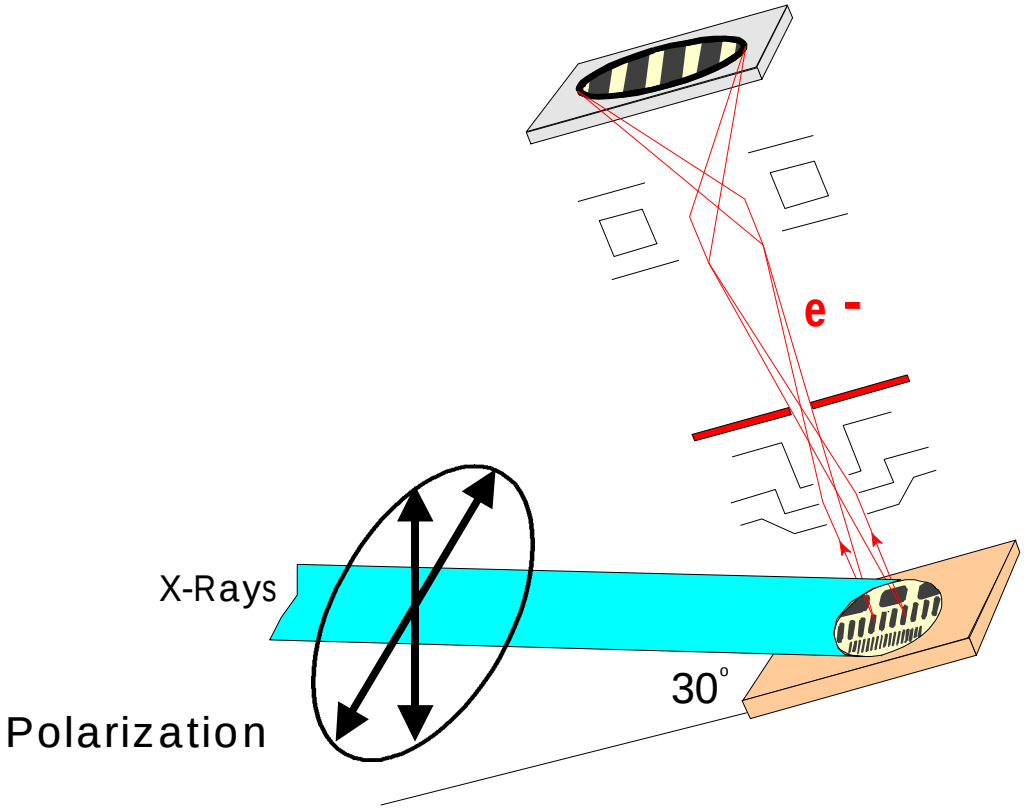
- Electric fields cause topographical contrast:



PEEM2 at the Advanced Light Source.

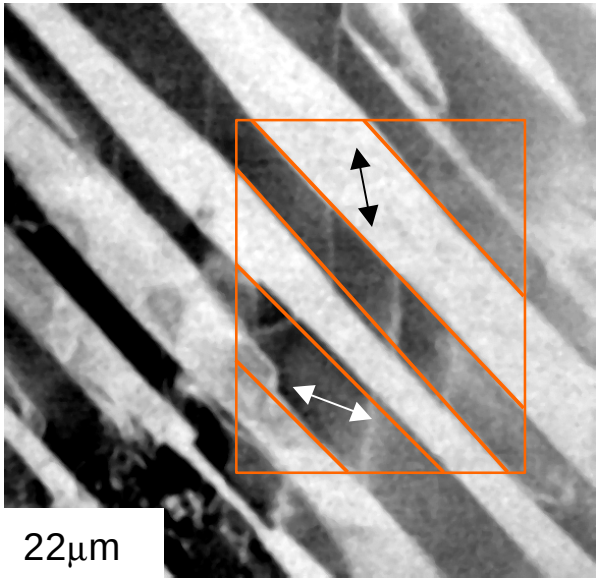
Full field x-ray absorption microscope

$E_{h\nu}$ = 250 - 1200eV, variable polarization.

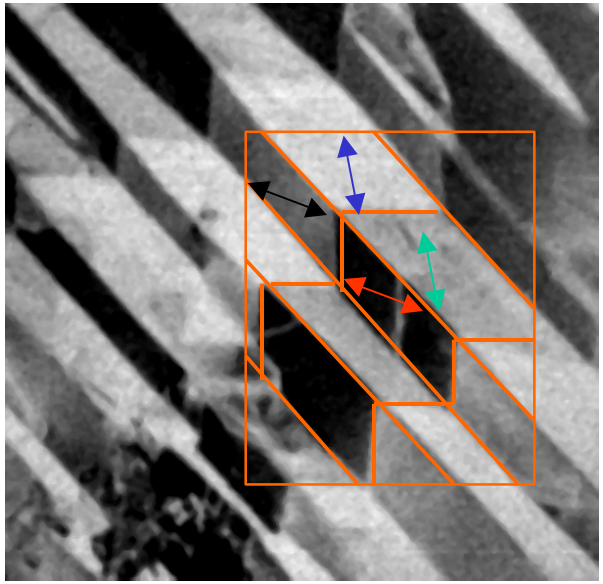


In Plane vers. Out of Plane -- AFM Domains on NiO(001)

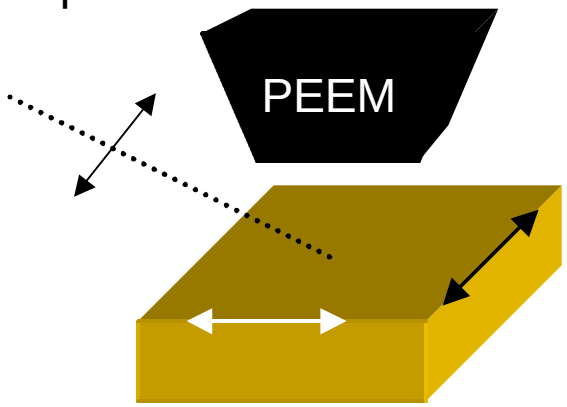
Linear polarization



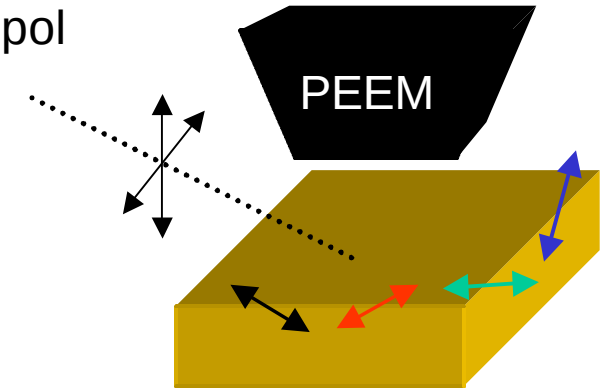
Plane polarization



π-pol



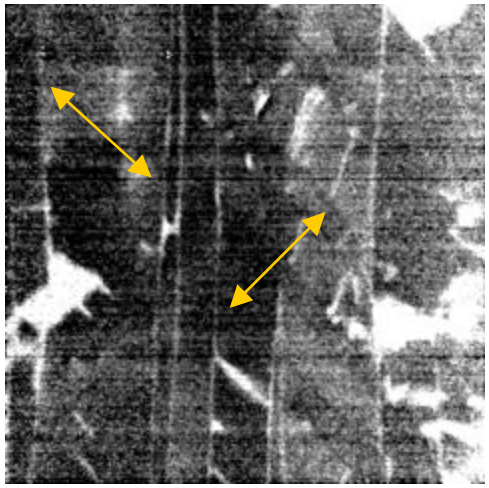
σ-pol

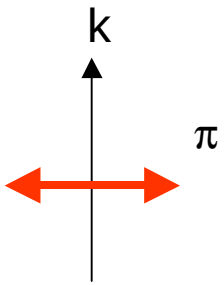


Distinguish out of plane AFM axes with out of plane polarization.

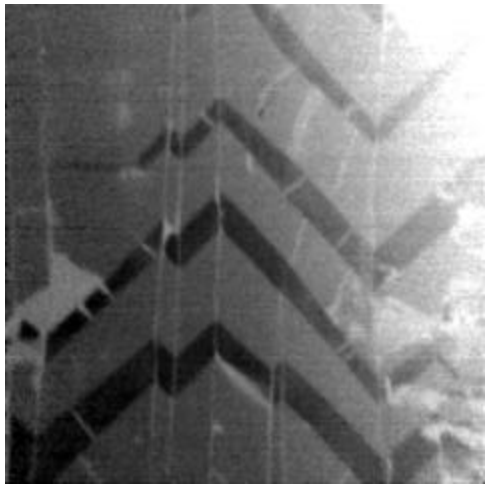
AFM axes on NiO(001)

Exact determination of XMLD intensity: Local XAS domain by domain

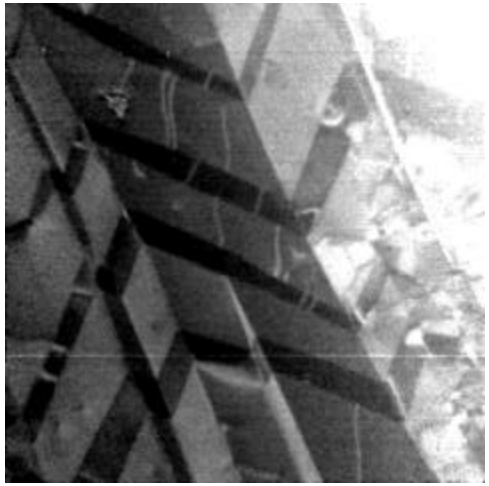




π determines inplane angle: +/-60 deg.



σ determines out of plane angle +/-35 deg.



Rotation
Some stripes get darker
some brighter.

Exact:

AXES : <121>

Using reference spectra for NiO the axes can be determined within +/- 5 deg.

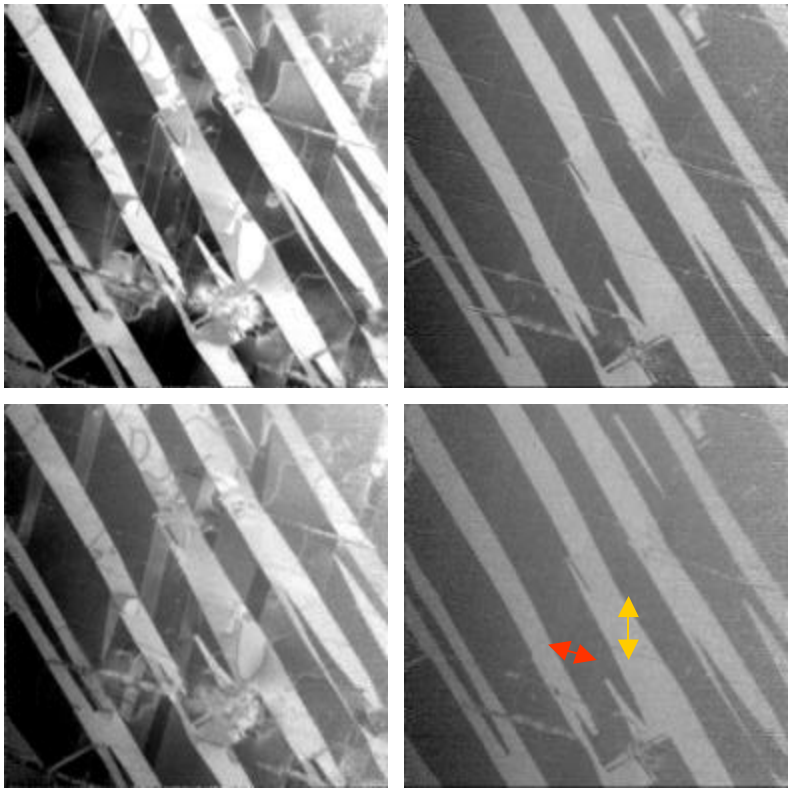
In Plane Reorientation upon Co Deposition NiO(001)

Bare

12 ML Co

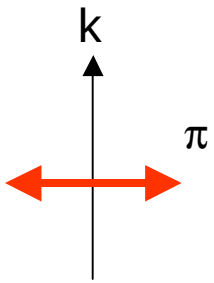
NiO

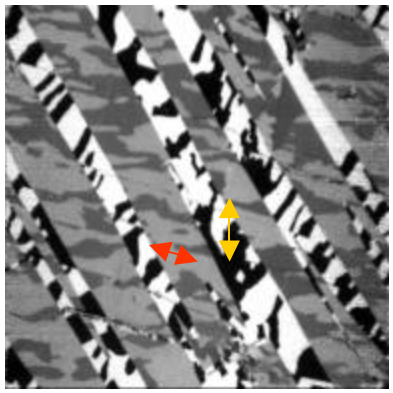
XMLD



Co

XMCD





π In plane

Contrast changes but not the pattern

σ Out of plane

Out of plane variation vanishes

Parallel orientation of FM and AFM axis

Now along <110>

XMLD Spectromicroscopy

In plane as well as out of plane distribution of antiferromagnetic order can be resolved with high accuracy and spatial resolution.

The depth dependence allows to characterize AFM order in buried films and at interfaces.

Easy when size of XMLD effect is already known